Flight test results from the Ultra High Resolution, Electro-Optical Framing Camera containing a 9216 by 9216 pixel, wafer scale, focal plane array

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ABSTRACT

The details of the fabrication and results of laboratory testing of the Ultra High Resolution Framing Camera containing on-chip forward image motion compensation were presented to the SPIE at Airborne Reconaissance XXII in 1998. Three airborne flight tests of the Camera system have since been conducted with excellent results. This paper summarizes predicted performance for the Camera and presents some of the flight test imagery and data.

Keywords: Reconnaissance, Mapping, Frame Camera, CCD, Electro Optical, Image Motion Compensation, Flight Testing

1. INTRODUCTION

Airborne reconnaissance missions require sensors with both high resolution and large fields of view. This is driven by the requirement to image targets such as mobile missile launchers which require large fields of view to find, and when partially obscured in defilade require high resolution to identify. As reconnaissance cameras have begun to move away from film and toward the use of electro-optical detector arrays there has been a constant strain on the ability of detector manufacturers to build arrays of sufficient size and resolution to replace film. In spite of the difficulties, the desire to produce electronic imagery which is readily manipulated and may be data linked in real time to multiple users continues to urge us on.

Due to image smear and vibration effects in reconnaissance platforms, film cameras typically achieve about 50 lp/mm resolution on film in flight (although film itself can produce greater resolution.) Film reconnaissance cameras use film sizes of 2.25, 5 and even 9 inches wide with a useable width of 2, 4.5 and 8.5 inches. At 50 lp/mm a single frame of imagery from one of these cameras contains from 5,000 x 5,000 to as high as 21,000 x 21,000 "pixels" of information. The most typical cameras using 5 inch film (4.5 x 4.5 inch frames) produce the equivalent of 11,000 x 11,000 pixels. The 9,216 x 9,216 pixel detector array described here was designed as a "replacement" for the capability offered by 5 inch film in the reconnaissance camera. Further, the array with its high resolution and large field-of-view reduces the need to step and stare a camera to achieve extended coverage as would be required with a smaller array.

2. DISCUSSION

The Detector Array

The detector array has been designed to maximize the pixel count achievable on a 5 inch diameter silicon wafer while preserving high yield. The key performance parameters and results from measured detector arrays are shown in **Table 1**.

The detector array meets all of the requirements needed to yield a high resolution, high frame rate reconnaissance camera. Most notable are the excellent charge transfer efficiencies in both the vertical and horizontal shift registers which allow high speed readout of up to two frames per second (while retaining high resolution image quality) and the combination of low noise and high conversion efficiency of the output amplifiers. Low noise allows for a very large dynamic range in the imager (>4,000:1). The high conversion gain keeps small signals above the noise floor of the high speed digital electronics.

Detector Array Architecture

The 9K detector array is a single monolithic matrix of 9,216 x 9,216 pixels each with the same unit cell supporting a 3- phase CCD readout. The 3-phase structure is not preferential and can shift charge in either of two directions, toward the "top" of the Array or toward the "bottom". Horizontal output registers have been located at both the top and the bottom of the array to allow shift in either direction. **Figure 3** Illustrates the array architecture.

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Table 1. Key Performance Parameters Of the 9K Detector Array	
Parameter	**Measured Value**
Pixel Count	9216 x 9216
Architecture	Full Frame
Pixel Size	8.75 x 8.75 micron
Operating Mode	Framing W/IMC
Frame Rate	> 2 Frames per Second
Vertical CTE	> 0.999999
Horizontal CTE	> 0.999995
Dark Current	< 70 pA/cm^2
Pixel Readout Rate	> 40 MPS
Readout Noise @ 25 MHz	< 25 e- rms
Conversion Gain	> 9 μV/e-
PRNU	< 5% Vsat
DSNU	< 1 mV
Quantum Efficiency	> 35% (0.55 to 0.8 nm)
Net MTF @ Nyquist	50%

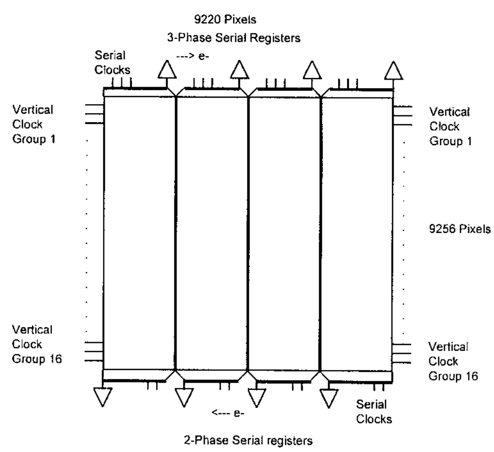


Figure 3. Array Architecture

To minimize peak vertical array clock currents, the array is driven by 16 groups of 3-phase vertical clocks and each group is pinned out at both sides of the array. This substantially reduces the capacitance that each external clock driver is required to drive, and reduces the RC clock paths down to that represented by 1/2 of the array width. All sixteen of the vertical clock sets can be driven in parallel from the same set of digitally generated clocks. Alternatively, for higher speed readout, eight sets can be run in such a way as to transfer charge to the top half of the array while the other set of eight clocks are run in such a way as to shift the charge out of the bottom half of the array. When operating in this way, the frame readout rate of the array is doubled.

The horizontal registers at the top and bottom of the detector array are each divided into four parts. Each part thus serves to read out 2,304 pixels. Including the top and bottom, there are a total of eight outputs from the array. Each output can be clocked at up to 40 MHz. Presently the clocks are set at 25 MHz thus producing a data output rate from the array of 200 million pixels per second! For initial test flights the Ultra High Resolution Camera will be operated at a maximum readout rate of one frame per second using the horizontal output registers at one end of the array. The resulting 100 Mega pixel per second data stream is compressed to 2.33 bits per pixel which yields a data rate (including annotation overhead) of less than 240 Mbps that is compatible with current digital tape recorders.

Array Packaging
The detector array is installed in a demountable and alignable package. The array is precision mounted within the package to a flatness specification of +/- 0.5 mils. This allows operation with F#s < 2 while retaining acceptable focus over the entire array.

Charge Transfer Efficiency
It is extremely important for the array to have high Charge Transfer Efficiency (CTE), particularly in the vertical direction. During vertical shift to the bottom of the array, image data must be moved through 9216 pixels to reach the horizontal output register. In the 3-phase structure of the vertical register, three shifts are required to move the charge one pixel. Transferring an image pixel from the top of the array to the bottom and into the horizontal register requires 9,216 x 3 or 27,648 shifts. Vertical charge transfer efficiency for the Ultra High Resolution Detector Array has been shown to be 99.9999%. Thus only 0.0001% of the image pixel's charge is left behind for each shift. Over 27,648 shifts the pixel from the top of the array will only leave behind 2.7% of it's charge. The horizontal register CTE is slightly less critical because data only moves through 1/4 the number of pixels to reach the output amplifier and two phase clocking is used. The measured horizontal CTE of 99.995% leaves behind 2.2% of the charge from the last pixel.

In both the vertical and horizontal registers the amount of charge left behind for the worst case pixel is extremely small. This is critical because the charge that is left behind reduces the signal in the pixel of interest and adds to the signal in the next trailing pixel. This will effectively reduce the contrast transfer function of the resultant output image. If for example, a high contrast pattern of alternating clear and opaque stripes, at the Nyquist spatial frequency, oriented parallel to the rows of the detector, were projected onto the array at 100% contrast, and phased so that the stripes were centered on the detector array pixels, the contrast transfer function (CTF) of the input pattern would be 100% as defined by the expression:

$$CTF = (Max - Min) / (Max + Min)$$

Where:
CTF = Contrast Transfer Function (Square Wave MTF)
Max = The signal level in the bar with Maximum brightness
Min = The signal level in the bar With Minimum brightness
Assumes Linear, Lossless Systems

The signal levels in a CCD detector array are typically expressed as numbers of electrons. In this case if Max started out as 1,000 electrons and Min as zero the CTF equals 100%. After shifting through the array the last pixel pair will have 973 electrons in the Max pixel and 27 electrons in the Min pixel. The resultant CTF is 94.5% for a loss in CTF of 5.5%. This is relatively insignificant and the Ultra High Resolution Imager shows excellent CTF from top to bottom

Total performance of any electro-optical system is typically determined by cascading the Modulation Transfer Functions (MTFs) from all uncorrelated, linear sources. MTF is sine wave response whereas CTF is square wave response. Since it is usually easier to produce bar targets that are square waves, response measured using square wave targets is mathematically converted to sine wave response. For a CCD at Nyquist, multiplying the CTF by $\pi/4$ is a sufficiently accurate conversion. Applying this conversion to the CTF at the midpoint of the detector array (half the shifts), the average loss in MTF in the vertical direction is 2%.

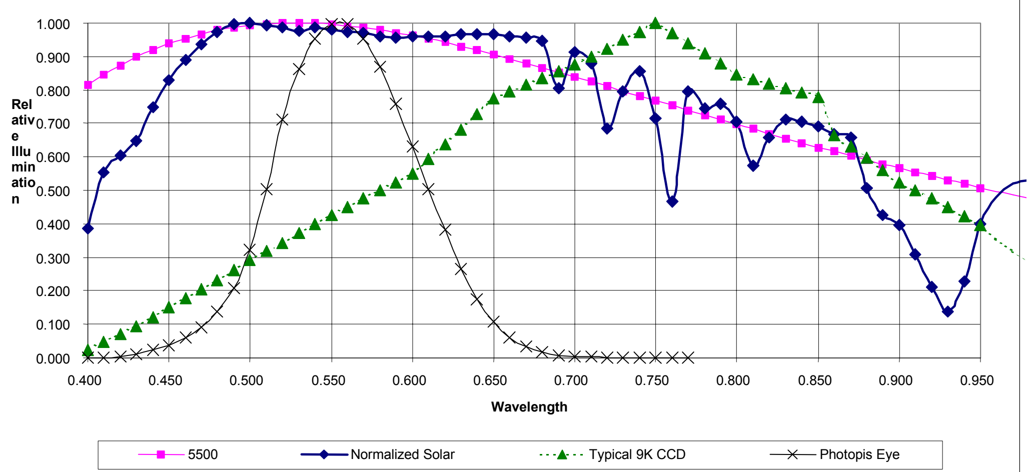
Seamless Imagery
Reconnaissance imagery requires a high level of confidence that complete scene coverage is achieved without artifacts. This is met by the wafer scale Ultra High Resolution detector with no seams or discontinuities between the sections of the imagery that are read by each of the horizontal registers. The CCD layout within the body of the detector array makes no distinction between any of the 9,216 columns of pixels. During readout, every pixel is picked up by one or another of the horizontal output registers.

Cascaded MTF Factors
The overall MTF Specification for the detector array is >50% for all sources cascaded. Contributors to MTF reduction in the detector array include the effects of sampling, CTE and Optical Crosstalk. Sampling MTF at the Nyquist frequency is 0.64 and the effects of CTE produce an average MTF of 0.98. This leaves a budget of 0.8 for Optical Crosstalk. Optical Crosstalk occurs when incident photons penetrate deeply into the CCD array before generating a corresponding photoelectron. Photoelectrons which are generated deep within the array must drift up to the potential wells on the surface

and may not be collected within the pixel area where the photon struck. Thus, the incoming signal is partially spread to adjacent pixels. Within silicon, longer wavelengths, such as those from 0.7 to 0.9 microns, penetrate more deeply creating more crosstalk. Unfortunately these are also the wavelengths where the detector array continues to have high quantum efficiency and the atmosphere is more transmissive. Hence we do not wish to filter them. Thinning and backside illuminating the array is one method of dealing with this problem but excessively costly in all but the most demanding applications.

However, the Ultra High Resolution Array architecture is a careful balance of well depth, oxide thickness and the use of Non MPP operation which yields the best balance of charge handling capacity, transfer speed and minimized crosstalk. The array meets the overall specification of 50% MTF when illuminated with white light bar patterns at a color temperature of 5500 K^o. This color temperature produces energy in the spectrum which closely matches that of direct sunlight. **Figure 5** Illustrates the energy distribution of 5500 K^o light, sunlight, the normalized response of a typical UHR detector array and Photopic Eye Response.

Figure 5. High Sun Angle Solar Illum after Two passes through atmosphere vs Black Body
Typical UHRS9K CCD Response and Photopic Eye Shown For Reference



Camera Block Diagram

A block diagram of the flight test camera and the associated airborne electronics units is shown in **Figure 6**. Separate electronics units include the Camera Body Unit (CBU), Imaging Electronics Unit (IEU), the Processing Electronics unit (PEU), the Tape Recorder Electronics Unit (REU), the Tape Transport Unit (TTU) and optional use of either the AN/ASQ-197 interface with cockpit control panel or a Laptop computer control unit.

The CBU contains interchangeable camera lens units and an improved high performance shutter.

The IEU attaches to the CBU. The IEU contains the detector array and all required drive electronics for the array. Four to eight channels of high bit rate, 12 bit per pixel, digital data are output from the unit. The IEU measures 10.32" long by 13.12" wide by 2.62" high.

The PEU performs all control functions, array signature correction, data compression and recorder interface. Control functions include exposure time calculation, frame rate and Image Motion Compensation clock rates. The PEU measures 8.38" long by 15" wide by 9.19" high. Array signature correction performed in the PEU reduces signature "noise" in the output video which is usually difficult for data compressors to handle. Elimination of this noise in the camera electronics allows for more compression with less error.

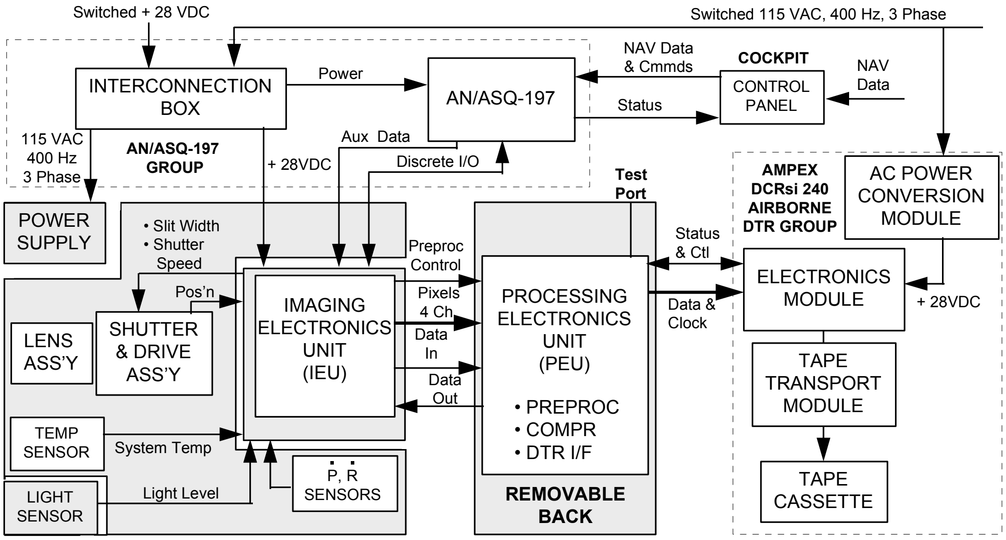


Figure 6. Ultra High Resolution Framing Camera Airborne System Block Diagram

Hardware

The fully integrated test camera including the associated processing electronics unit and digital data recorder is shown in **Figure 7**.

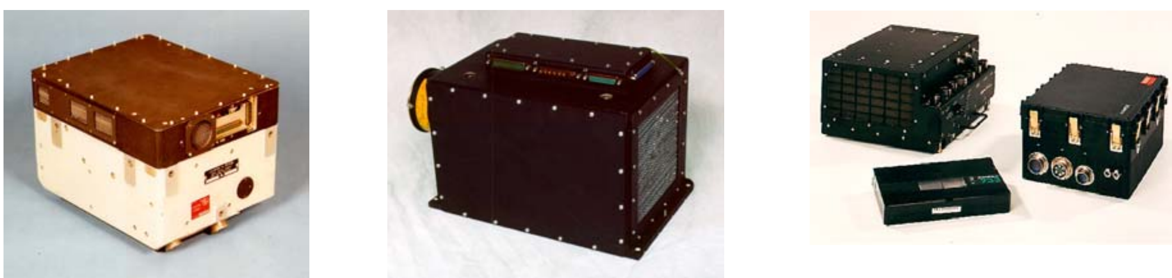


Figure 7. Ultra High Resolution Imaging Unit, Processing Electronics Unit and Digital Tape Recorder.

Electronic Image Motion Compensation

Image motion compensation or a very short exposure time is needed to produce an effective airborne reconnaissance camera. The Ultra High Resolution EO Framing Camera uses continuously graded on-chip motion compensation in conjunction with a focal plane shutter to allow operation from bright sunlight to dawn/dusk with exposure times typically between 1/3000 sec to 1/100 sec.

IMC Method

The use of Charge Coupled Devices in place of film allows for a new method of "electronic" image motion compensation. In this method, the electronic signal being formed in the detector array by the image can be shifted to move along with the motion of the image falling on the array by activating the normal vertical clock readout sequence during the exposure (TDI.)

Using the Focal Plane Shutter Slit

Forward image motions are not the same at all positions in the field of view. In order to solve the problem of non-uniform image motion as a function of position of the object being photographed, it is necessary to alter the charge motion rate for each column (or group of columns). A simple way of accomplishing this is to keep the readout charge motion rate uniform throughout the entire array and to continuously vary the uniform rate as a function of that portion of the imager which is being exposed by the open slit in a focal plane shutter at any given instant.

When a focal plane shutter is used, only a portion of the array is exposed at any one time through the moving slit of the shutter. Thus, if one matches the charge motion rate with the position of the slit as it traverses the chip, the optimum charge motion rate can be utilized for the exposed portion of the array. Since only one area of the array is exposed during the time associated with a given charge transfer rate, a nominally ideal image motion compensation can be obtained on-chip. This is referred to as continuously graded IMC. **Figure 8** illustrates the graded IMC concept as it would be used in the forward oblique imaging mode. The concept applies equally well in side oblique or vertical orientations. In side oblique applications the shutter is reoriented with respect to the array so that the vertical shift direction aligns with the slit length.

In any application the rate of change of charge motion is smooth and continuous with no segmenting or discontinuities. Thus, by taking advantage of the “metering” of imagery onto the array by the slit and the typical array readout process, image motion compensation is achieved.

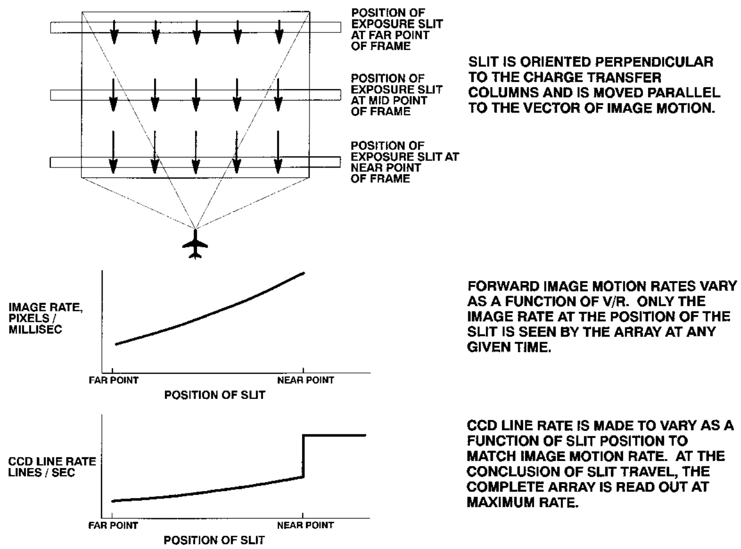


Figure 8. Operation of Graded IMC in the Forward Oblique mode.
Ideal matching of the image motion and charge motion is achieved by simply varying the vertical readout clock rate during the exposure interval.

3. FLIGHT TESTS

Three flight tests have been accomplished thus far to validate performance predictions of the Ultra High Resolution Reconnaissance Imager. The general test conditions for the flights are shown in **Table 2**. An index of the images extracted for evaluation from the Flight Tests provided in **Table 3 and Table 4**. Space precludes printing samples of all the images listed.

Nyquist Resolution Test Flight

In the second flight test of the Framing Camera System, test targets on the ground were imaged at relatively high V/H. This tested both the basic resolving power of the imager as well as operation of the on-chip forward motion compensation. **Figure 9** shows the full field-of-view and a 12:1 zoom of the image which is listed in **Table 3** as the “Low Overflight Test Target”. The direction of flight in the image is from bottom to top. **Table 5** provides the ground resolution for the test target. The target has standard 5:1 aspect tri-bar groups increasing in resolution at the standard sixth-root-of-two progression. The lowest resolution group is in the upper left of the target board shown in **Figure9** and the increasing resolution target groups may be counted along the “spiral” in clockwise fashion. The tri-bar that correcponds to the Nyquist resolution of the sensor from the altitude of approximately 300 feet is between groups 27 and 28. Groups 27 and 28 represent 3 and 2.67 inches respectively. Nyquist resolution of the sensor, based on scaling the target board, is 2.74 inches at 57.5 lp/mm (The total target board is 80 inches wide and is subtended by 701 pixels, yielding 1.37 inches per pixel.) Nyquist resolution is clearly obtained in enlargements of the image. Measured MTF of the Target board image yields 28.5% in the in-track direction and 25.5% in the cross track direction.

Table 2. General Data From Flights 1, 2 and 3	
Item	**Description**
Aircraft	BAC-111
Camera System	Ultra High Resolution Framing Camera, 9216 x 9216 pixel Framing Detector Array employing on chip Forward Motion Compensation. Flown with 12-inch focal length and 1-inch focal length lenses.
Spectral Sensitivity	Flight 1 and 2, 0.45 to 0.95 micron wavelength. The near IR (0.75 to 0.95 µm) sensitivity of the array gives rise to the white appearance of the foliage and grass. Flight 3 used a KG3 filter to restrict the spectrum to the photopic region. Foliage and grass appear dark.
AGC	The Camera employs an Automatic Gain Circuit that always sets the brightest areas of the scene to a digital level of 245. The algorithm acts continuously from the start of the picture to the end with a time constant of several hundred lines. The algorithm spans all four output segments of the array.
Ground Footprint at 3,000 ft. Altitude, 30° Depression Angle, 12-inch Focal Length Lens	Ground Range To: Near point 3,905 ft., Far point 7,255 ft Along track FOV: At Near point 1,303 ft., at Far point 2,077 ft. Slant Range To: Far point 7,840 ft., 1/8 down 7,269ft., 1/4 down 6,783 ft., 3/8 down 6,364 ft., 1/2 down 6,000 ft., Nearest point 4,924 ft.
Ground Footprint at 300 ft., Vertical, 1-inch Focal Length Lens	Ground FOV is approximately 950 x 950 feet.
Airborne System	Camera, Real-Time Hardware VQ Data Compressor, 240 Mbps Digital Data Recorder
Playback System	Digital Data Recorder, Hardware Data Decompressor, Sun Workstation with Electronic Light Table Software and Display. Images converted to TIF format for universal dissemination.
Target Area Flight 1	U.S. Naval Academy. Annapolis MD, Latitude Longitude N38° 59 ft., W76° 29 ft.
Target Area Flight 2	Webster Field VA. Latitude Longitude N38° 08 ft., W76° 26 ft.
Target Areas Flight 3	Washington Capitol Building, Washington Mall, Washington Monument, Pentagon, Langley AFB, Norfolk VA, Oceana

FMC correction

The MTF of the one inch optics are about 60% for full spectrum illumination at 57.5 lp/mm. The array MTF as previously indicated is 50%. The forward image motion for the flight conditions was 3.6 pixels of smear per millisecond. The exposure time was 1/2000th of a second. During the 1/2000th second exposure, an uncorrected image would smear 1.8 pixels. The MTF at Nyquist from such a smear would be 10%. If this were left uncorrected, the total system MTF would be 3% at Nyquist. Measured MTF data actually matches the expected total from the optics and array contributions without image motion (30%). In addition, the MTF in the in-track direction, the direction that would be effected by the motion smear, was better than the cross track MTF. These test results verify proper operationm of the on-chip FMC as well as overall system MTF performance.

Table 3. Index Of Images From Ultra High Resolution Framing Camera Flight Tests #1 and #2									
Flt#	**Image Descriptor**	**# Pix horix**	**# Pix vert**	**Focal Length (in)**	**Altitude (Ft)**	**Airspeed (Kn)**	**Net Depression Angle (Deg)**	**Slant Range to Center (Ft)**	**COF Fwd Mot Pix/ms**
1	Top 50% Of Clock Tower Frame	9216	4608	12	3000	250	30	7269	2.02
1	Enlarged Clock Tower Area	1010	1160	12	3000	250	30	7269	2.02
1	Clock Enlarged	540	430	12	3000	250	30	7269	2.02

1	Top 50% Of Mid Academy	9216	4608	12	3000	250	30	6783	2.17
1	Center Buildings Enlarged	2560	2950	12	3000	250	30	7269	2.02
1	Truck Enlarged	1300	890	12	3000	250	30	7940	1.85
1	Top 75% Of Academy Marina	9216	6912	12	3000	250	30	6364	2.31
1	Enlargement of Men at Marina	530	550	12	3000	250	30	6364	2.31
1	Stereo Section (right) from ULS	3000	5000	12	3000	250	30	6783	2.17
1	Stereo Section (left) from URS	3000	5000	12	3000	250	30	6783	2.17
2	Low Overflight of Test Target	9216	9216	1	300	220	90	300	3.59
2	Enlarged Test Target	930	890	1	300	220	90	300	3.59
2	Enlargement of Missile Launchers	1329	793	1	300	220	90	300	3.59
2	Enlargement of Tanks	1595	1261	1	300	220	90	300	3.59
2	Man On Tractor	1595	1261	1	300	250	90	300	4.08
2	House	1595	1261	1	300	250	90	300	4.08

Table 4. Index Of Image Areas From Ultra High Resolution Framing Camera Flight Test #3

Target Leg Descriptor	Altitude (Ft)	Airspeed (Kn)	Depression Angle (Deg)	Focal Length (in)	SlantRange toCenter (Ft)	COF Fwd Mot Pix/ms
Capital	6000	250	30	12	12000	1.23
Mall	6000	250	30	12	12000	1.23
Momemunt	6000	250	30	12	12000	1.23
Pentagon	6000	250	30	12	12000	1.23
Capital	10500	350	30	12	21000	0.98
Mall	10500	350	30	12	21000	0.98
Washington Momument	10500	350	30	12	21000	0.98
Richmond	3000	250	30	12	6000	2.45
Langley	3000	250	30	12	6000	2.45
Norfolk	3000	250	30	12	6000	2.45
Oceana	3000	250	30	12	6000	2.45

Table 5. Tri Bar Target Dimensions. Groups progress clockwise from low resolution to high resolution

Bar Group	Size (Inches)			GRD (in)	Bar Group	Size (Inches)			GRD (in)
	Horiz.	By	Vert.			Horiz.	By	Vert.	
1	151.25	X	30.25	60.5	20	16.84	X	3.37	6.74
2	134.7	X	26.95	53.90	21	15.01	X	3.00	6.00
3	120.0	X	24.01	48.02	22	13.37	X	2.67	5.35
4	106.9	X	21.39	42.78	23	11.91	X	2.38	4.76
5	95.3	X	19.06	38.11	24	10.61	X	2.12	4.24
6	84.9	X	16.98	33.95	25	9.45	X	1.89	3.78
7	75.6	X	15.13	30.25	26	8.42	X	1.68	3.37

8	67.4	X	13.47	26.95	27	7.50	X	1.50	3.00
9	60.0	X	12.00	24.01	28	6.68	X	1.34	2.67
10	53.5	X	10.69	21.39	29	5.96	X	1.19	2.38
11	47.6	X	9.53	19.06	30	5.31	X	1.06	2.12
12	42.4	X	8.49	16.98	31	4.73	X	0.95	1.89
13	37.8	X	7.56	15.13	32	4.21	X	0.84	1.68
14	33.7	X	6.74	13.47	33	3.75	X	0.75	1.50
15	30.0	X	6.00	12.00	34	3.34	X	0.67	1.34
16	26.7	X	5.35	10.69	35	2.98	X	0.60	1.19
17	23.8	X	4.76	9.53	36	2.65	X	0.53	1.06
18	21.2	X	4.24	8.49	37	2.36	X	0.47	0.95
19	18.9	X	3.78	7.56	38	2.11	X	0.42	0.84

Seamless Imagery

Figure 10 is a full field of view image of the Capitol Building Region in Washington D.C. Although the image is read from the detector array using four separate amplifiers no difference between the image sections is discernable at this level of displayed resolution. An area of the image spanning the locus of pixels which split into two different amplifiers during readout of the array is outlined by a square.

Figure 11 provides an enlargement of the highlighted area from the image of the Capitol Building Region. There is no image discontinuity at this boundary. A very slight variation in signal level extending one pixel away from the boundary and varying slightly as a function of the local illunimnation level can occasionaly be seen. No information content is lost. This slight effect may be created by some charge injection at the edge of the tapered readout register.

4. SUMMARY

Flight testing has validated the performance predicted for the Ultra High Resolution Reconnnaissance camera. The MTF meets specification and the on-chip FMC method is proven. Seamless, high quality imagery is produced in instant digital format.

5. ACKNOWLEDGMENTS

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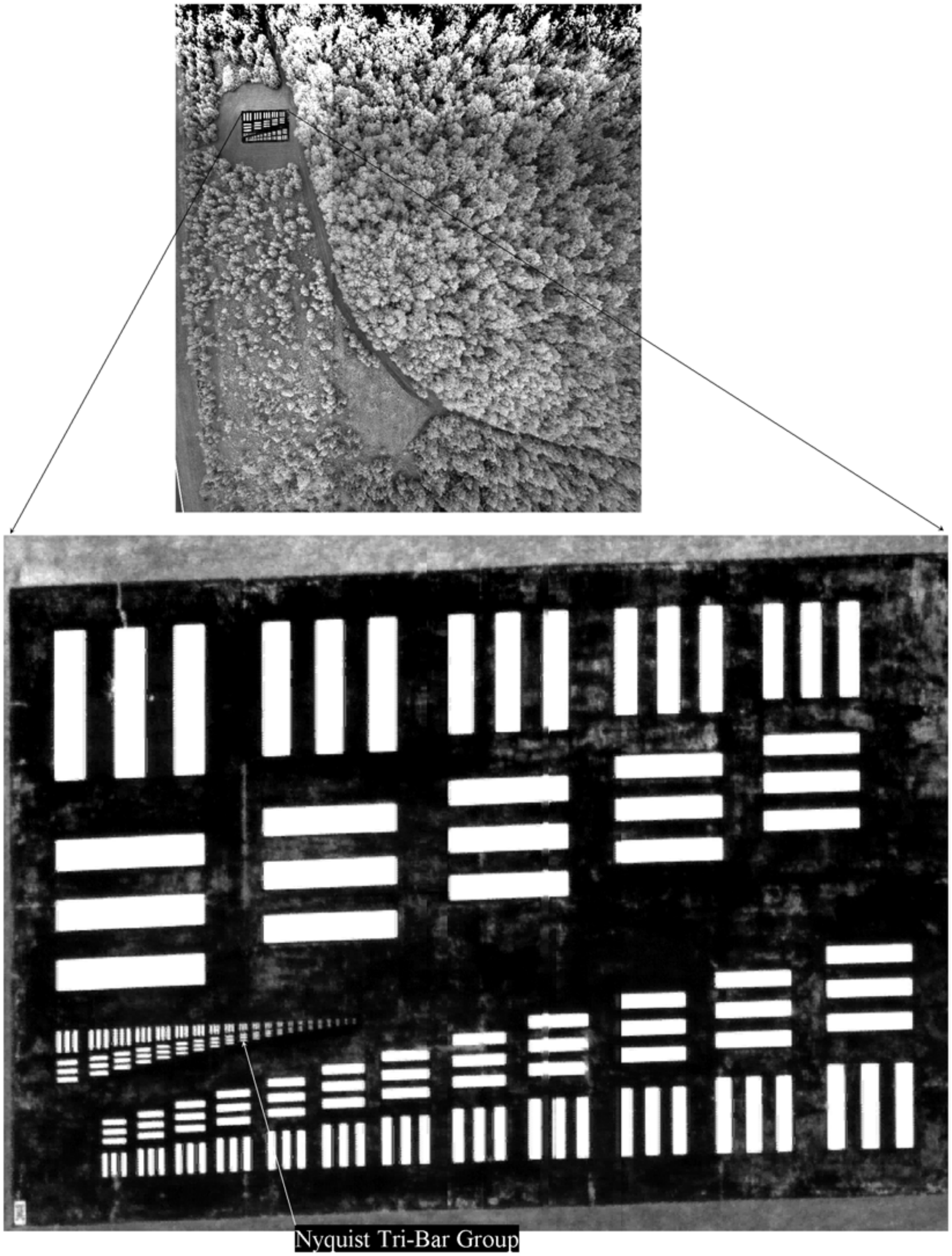

Figure 9 Low Overflight Test Target Image Showing Full FOV and 12:1 Zoom of The Target Area

Figure 10. Full Field Of View Image of the Capitol Building Area of Washington D.C. Taken During Test Flight #3 By the Ultra High Resolution Framing Camera.

Figure 11. Enlargement Of the transition point between array output sections.